STUDY OF FINGERPRINT RECOGNITION SYSTEM

IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS

FOR THE DEGREE OF

Bachelor of Technology

In
Electronics and communication Engineering

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CERTIFICATE

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ROURKELA

This is to certify that the thesis entitled, “FINGERPRINT RECOGNITION” submitted by Tatsat Naik and Om Sri Satyasai in partial fulfillments for the requirements for the award of Bachelor of Technology Degree in ELECTRONICS & COMMUNICATION ENGINEERING at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision and guidance.

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ABSTRACT

Human fingerprints are rich in details which is known as minutiae, which can be used as identification marks for fingerprint verification. Our term project is to study on fingerprint recognition system based on minutia based matching which is quiet frequently used in various fingerprint algorithms and techniques. The approach of this project involves how the minutia points are extracted from the fingerprint images and after that between two fingerprints we are performing the fingerprint matching. Image enhancement, image segmentation, minutia extraction and minutia matching these stages are the main themes of our project. This project is coded in MATLAB.

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CHAPTER 1

INTRODUCTION

1. INTRODUCTION

Basically Skin of human fingertips consists of ridges and valleys and they mixing together form the distinctive patterns. At the time of pregnancy these distinctive patterns are fully developed and are permanent throughout the whole lifespan. Those patterns are called fingerprints. From different researches it has been observed that no two persons have the same fingerprints, so they are unique for each individual .because of the above mentioned characteristic, fingerprints are very popular for biometrics applications. Finger print matching is a very complex pattern recognition problem so Manual finger print matching is not only time taking but experts also takes long time for education and training.

Fingerprints have remarkable permanency and uniqueness through out the time. From observations we conclude that the fingerprints offer more secure and reliable personal identification than passwords, id-cards or key can provide. Examples such as computers and mobile phones equipped with fingerprint sensing devices for fingerprint based password protection are being implemented to replace ordinary password protection methods.

1.1 Fingerprint

A finger prints are the most important part of human finger. It is experienced from the research that all have their different finger prints and these finger prints are permanent for whole life. So fingerprints have been used for the forensic application and identification for a long time.

Figure 1.1.1 Finger print image acquired by a Sensor

A fingerprint is the composition of many ridges and furrows. Finger prints can't distinguished by their ridges and furrows. It can be distinguished by Minutia, which are some abnormal points on the ridges.

Minutia is divided in to two parts such as: termination and bifurcation. Termination is also called ending and bifurcation is also called branch. Again minutia consists of ridges and furrows. valley is also referred as furrow

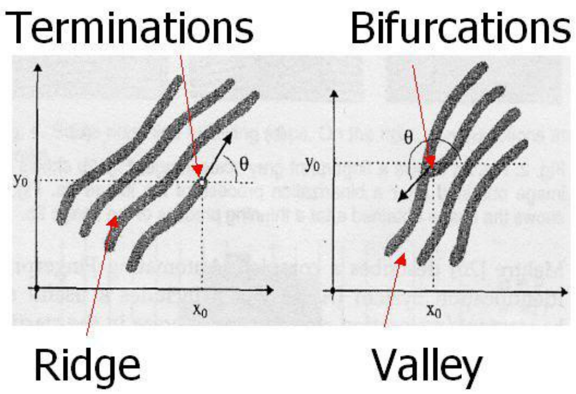


Figure 1.1.2 (DIAGRAM OF MINUTIA)

1.2 finger print recognition:-

The fingerprint recognition problem can be grouped into two sub-domains such as:-

i) fingerprint verification ii) fingerprint identification (Figure1.2.1).

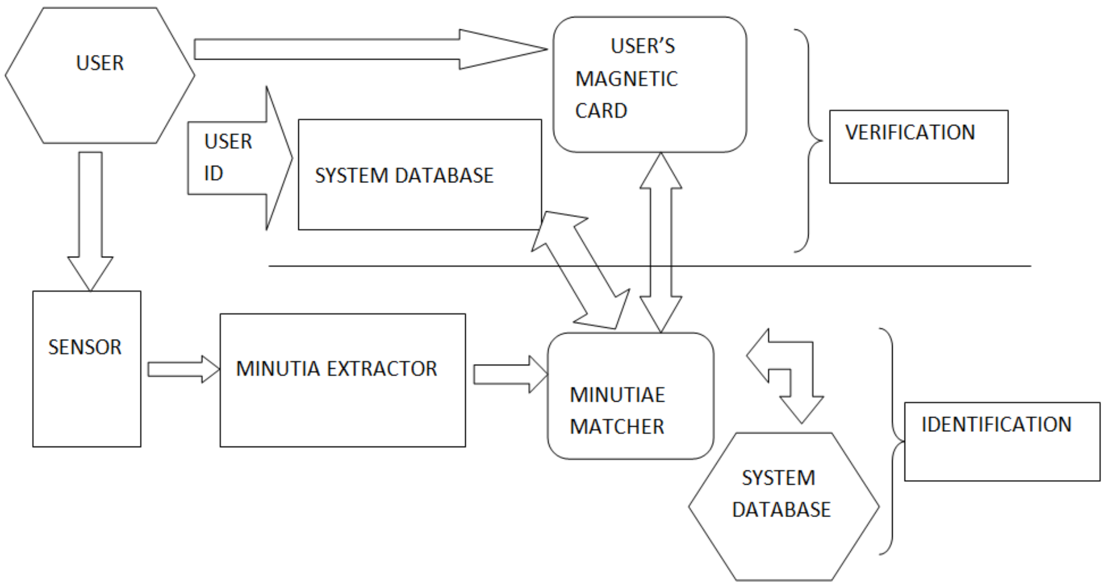


Figure 1.2.1

Fingerprint verification is the method where we compare a claimant fingerprint with an enrolee fingerprint, where our aim is to match both the fingerprints. This method is mainly used to verify a person's authenticity. For verification a person needs to his or her fingerprint in to the fingerprint verification system. Then it is representation is saved in some compress format with the person's identity and his or her name. Then it is applied to the fingerprint verification system so that the person's identity can be easily verified. Fingerprint verification is also called, one-to-one matching.

Fingerprint identification is mainly used to specify any person's identity by his fingerprint. Identification has been used for criminal fingerprint matching. Here the system matches the fingerprint of unknown ownership against the other fingerprints present in the database to associate a crime with identity. This process is also called, one-to many matching. Identification is traditionally used for solve crime and catch thieves.

CHAPTER 2

SYSTEM LEVEL DESIGN

2.1 System level design:-

Here a fingerprint recognition system contains a sensor, minutia extractor and minutia matcher [Figure 2 (a)].

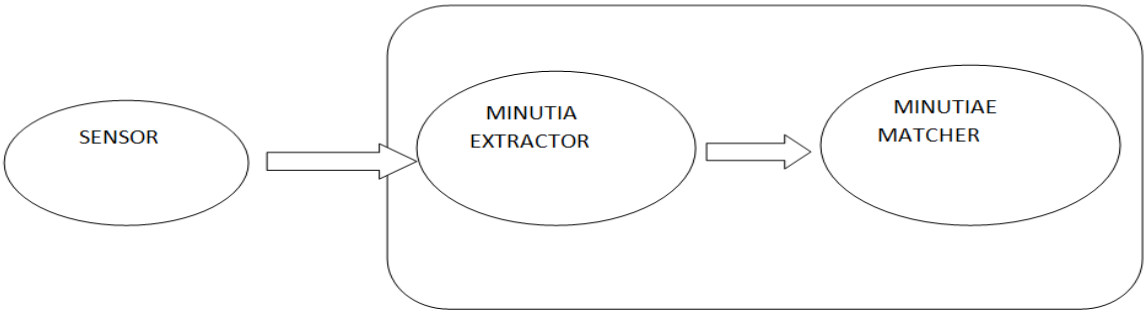


Figure 2.1 (a)

Optical and semi-conduct sensors are mainly used in fingerprint acquisition system. These sensors are of highly acceptable accuracy and high efficiency except for some cases like if the user's finger is too dirty or dry.

To extract a minutia a three step approach is used such as:- i) pre processing stage ii) minutia extraction stage iii) post processing stage.

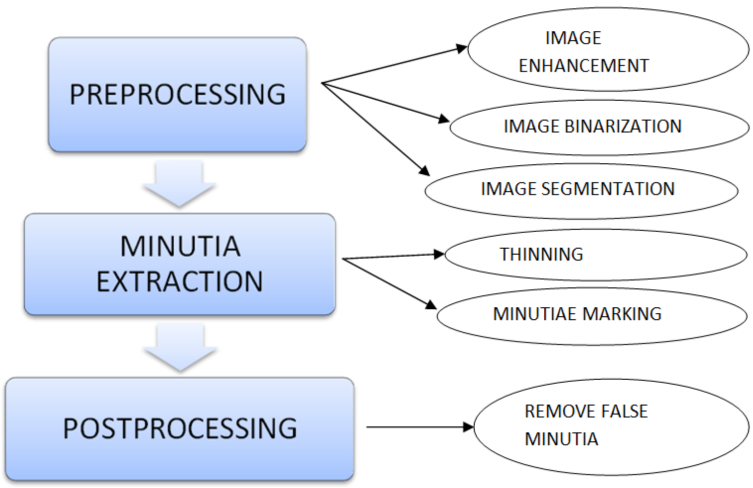


Figure 2.1 (b) [Minutia extractor]

2.1.1 Pre processing stage:-

Again pre processing stage is divided in to three sub stages such as:- i) image enhancement ii) image binarization iii) image segmentation. For image enhancement we used two methods such as:- histogram equalization and Fourier transform. After enhancing the image we need to binaries the image for that we used the locally adaptive threshold method.

For image segmentation we preferred a three-step approach such as :- i) block direction estimation ii) segmentation by direction intensity iii) Region of Interest (ROI) extraction by Morphological operations.

2.1.2 Minutia extraction:-

Minutia extraction stage is divided in to two sub stages such as:- i) fingerprint ridge thinning and ii) minutia marking We used iterative parallel thinning algorithm for minutia extraction stage. Ridge thinning is used to used to eliminate the redundant pixels of the ridges till the ridges are of one pixel wide.The minutia marking is quite simple task. Here crossing number (CN) concept is used.

2.1.3 Post processing stage:-

For the post processing stage, it has only one sub step that is:- removal of false minutia. Also a novel representation for bifurcations is proposed to unify terminations and bifurcation.

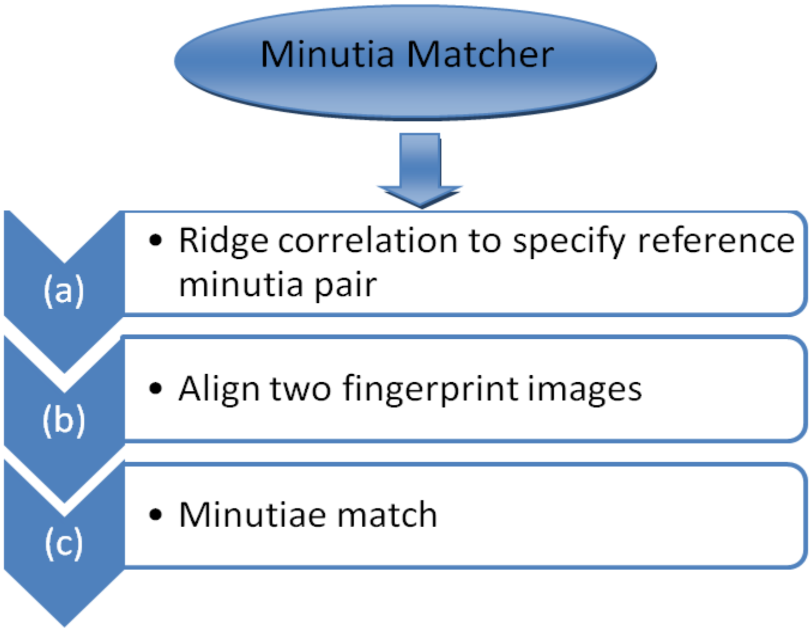


Figure 2.1 (c) Minutia matcher

The minutia matcher determines whether the two minutia sets are from the same finger or not. If the ridges are match well, then the two fingerprint images are aligned and matching is conducted for all remaining minutia.

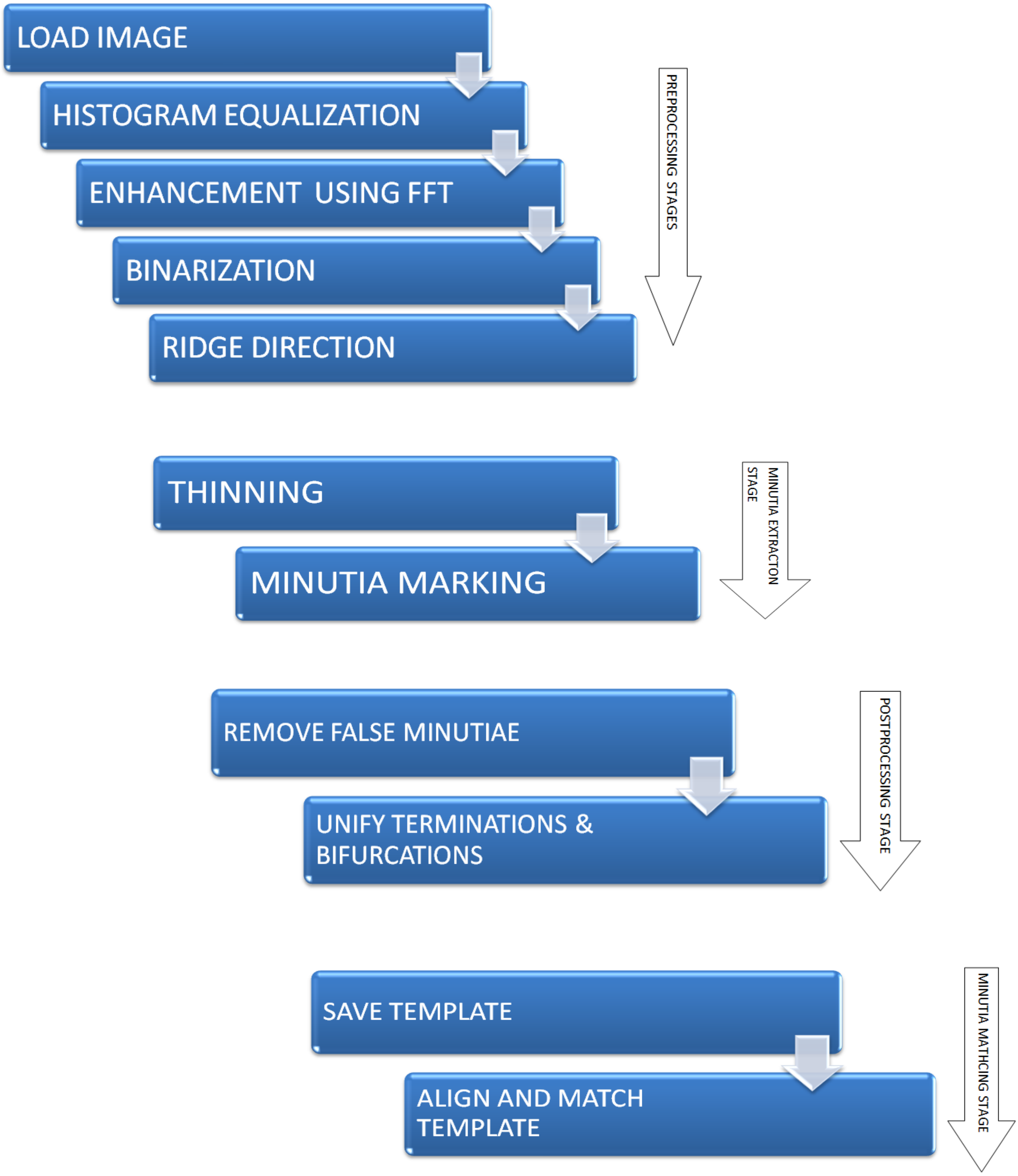


Figure .2.1 (d) One by one steps involved in fingerprint recognition algorithm

CHAPTER 3

PREPROCESSING STAGE

3.1 Fingerprint image enhancement

Fingerprint image enhancement is used to make image clear for better use which is very easy to handle and can operate easily for further operation. Basically a fingerprint image is full of noise. Because our fingers are often comes in contact with the most of the manual tasks we perform like fingertips become dirty, cut, scarred, creased, dry, wet, worn, etc. The image enhancement step is basically designed to reduce this noise and to enhance the definition of ridges against valleys.

Here we used two method for image enhancement stage those are:

I. Histogram Equalization

II. Fourier Transform.

3.1.1 Histogram equalization:-

Histogram equalization is mainly used to increase the pixel value of an image so that the perceptional information also increase. Histogram represents the relative frequency of various types of gray levels in an image. By using this method we can improve the contrast of an image and it is one of the most deserving technique in image enhancement. The original histogram of a fingerprint image is like a bimodal type after histogram it occupies the range from 0 to 255 and the visualization effect is also increased.

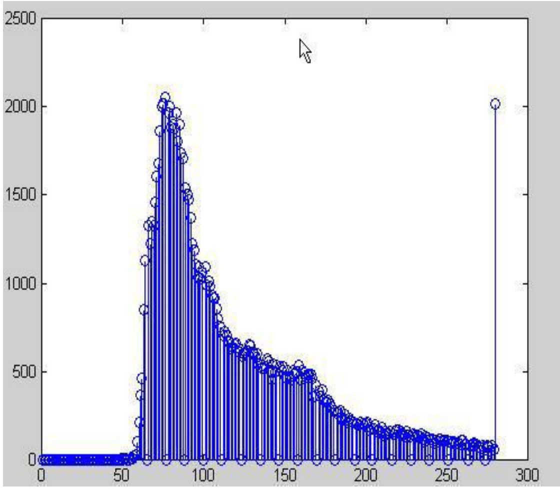


Figure 3.1.1.1
Histogram of a fingerprint image

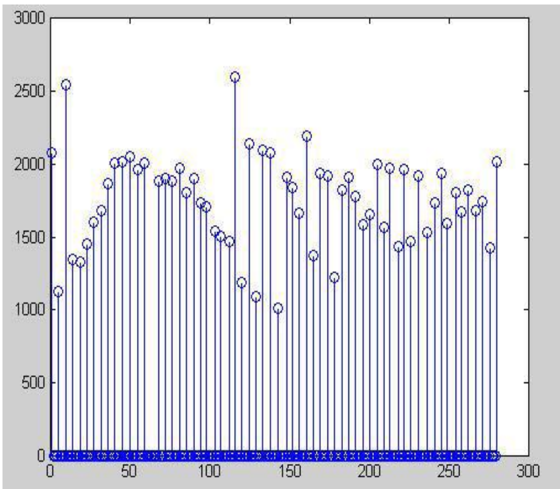


Figure 3.1.1.2
Histogram after histogram equalization

Figure 3.1.1.3 Original Image

Figure 3.1.1.4 Enhanced Image after Histogram Equalization

3.1.2 Fourier transform:-

Here first of all we divide the image into different small processing blocks those are of 32 by 32 pixels then use the Fourier transform according to formula:

$$F(u,v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) \times exp\left\{-j2\pi \times \left(\frac{ux}{M} + \frac{vy}{N}\right)\right\} \qquad (1)$$

For u = 0, 1, 2, ..., 31 and v=0, 1, 2, ..., 31

To enhance those small processing blocks through its dominant frequencies, we multiplied the FFT of the block with its magnitude a set of times.

Where the magnitude of the original FFT = abs(F(u,v)) = |F(u,v)|.

Now we get the enhanced block according to the formula:-

$$g(x,y) = F^{-1}\{F(u,v) \times |F(u,v)|^K\} \qquad (2)$$

Where F^{-1}(F(u,v)) is :

$$f(x,y) = \frac{1}{MN} \sum_{x-0}^{M-1} \sum_{y-0}^{N-1} F(u,v) \times exp\left\{j2\pi \times \left(\frac{ux}{M} + \frac{vy}{N}\right)\right\} \qquad (3)$$

For x = 0, 1, 2, ..., 31 and y = 0, 1, 2, ..., 31.

k is an experimentally determined constant used in equation(2), where we have taken the value of k=0.45 for the further calculation. If the value of “k” increases then the appearance of the ridges also increases and it is filling up small holes in ridges, if the value of “k” is too high then it may results false joining of ridges. Thus a termination might become a bifurcation. Figure 3.3.2 presents the image after FFT enhancement.

Figure 3.1.2.1 original image

Figure 3.1.2.2 Fingerprint Enhanced By FFT

After the enhancement of the image through FFT it is quite easy to connect the falsely broken points on ridges and it becomes simpler to remove some unwanted cross connections between ridges.

3.2 Fingerprint image binarization:-

In case of image binarization we basically binarize the image by extracting the lightness of the image that is here we extract the brightness and density of the image as a feature amount from the image. When we select a pixel in an image, A sensitivity is added to it and it is subtracted from the Y value of the selected pixel because here we have to set the range of threshold value. Next, when a new pixel is selected again a new threshold value range is set which contains the calculation result and the previous threshold value. Then the pixel is extracted up to the same brightness whatever the selected pixel and the extraction result is displayed. Fingerprint Image Binarization is used to transform the 8-bit Gray fingerprint image to a 1- bit image and here the value for the ridges is 0 where as it is 1 for the furrows. After these operation, the ridges in the fingerprint will be highlighted with black colour while furrows will be colour with white.

To binarize a fingerprint image we basically use a locally adaptive binarization method.

Figure 3.2.1 Enhanced Image

Figure 3.2.2 Image after Binarization

3.3 *Fingerprint image segmentation:-*

In case of segmentation we basically partitioning a digital image in to multiple segments that is a set of pixels, It also well known as super pixels. Our aim of the segmentation is to make the image simpler which can be represent very easily and to make the image meaningful so that it will be easy to analyze. Typically image segmentation is used to locate the objects and boundaries like the lines and curves present in an images. Generally Region of Interest (ROI) is very much useful for recognizing each fingerprint image. The image area without effective ridges and furrows holds background information. So the effective ridges and furrows deleted first. Then the remaining effective area is sketched. Because the minutia present in that region are too much confusing with other duplicate minutia which are created when the ridges are out of the sensor.

To extract the ROI, we used a two-step approach that is :- i) block direction estimation and direction variety check ii) intrigued from some Morphological methods.

3.4 Block direction estimation:-

Here in block direction estimation first of all we partition the fingerprint image in to different blocks of size 16 x 16 pixels (w x w). Then we calculate the block direction of each image by using the following rules:-

I. First of all we have to calculate the gradient values along the x-direction (g_x) and then along the y-direction (g_y) for every pixels present in the block. Here we used two Sobel filters to complete the task.

II. For getting the least square approximation of the block direction of all blocks we used the following formula :-

$$tan2ß = \frac{2\sum\sum(g_x{*}g_y)}{\sum\sum(g_x{}^2-g_y{}^2)}$$

III. For all the pixels in each block we used the following formula

$$tan2\theta = \frac{2sin\theta\, cos\theta}{cos^2\theta - sin^2\theta}$$

After finishing the estimation of each block direction, those blocks are deleted which don't have any significant information on ridges and furrows. That is done by using the following formula :-

$$E = \frac{2\Sigma\Sigma\,(g_x * g_y) + \Sigma\Sigma\ (g_x^2 - g_y^2)}{W * W * \Sigma\Sigma\ (g_x^2 + g_y^2)}$$

Here E is the certainty level. If its certainty level E is below the threshold, then the block is regarded as a background block.

Figure 3.4.1 (BINARIZATION IMAGE)

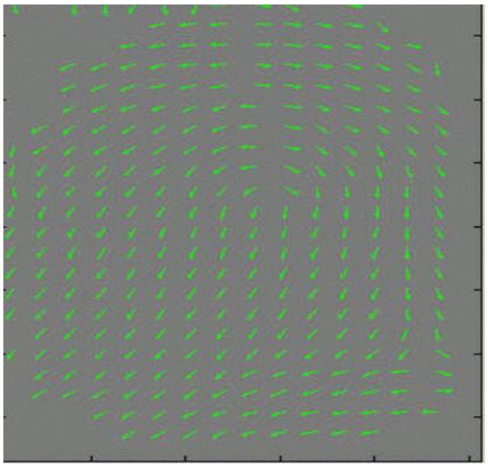


Figure 3.4.2(DIRECTION MAP)

3.5 ROI Extraction by morphological operations:-

ROI extraction can be done using two Morphological methods those are OPEN and CLOSE. By using the OPEN operation we can enhance images and remove the peaks caused by background noise and we use 'CLOSE' operation to shrink the images and to eliminate the small cavities.

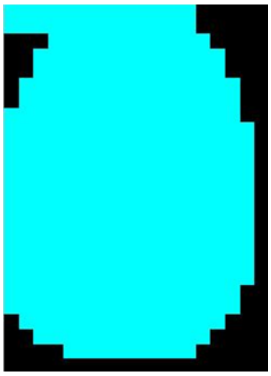


Figure 3.5.1 ORIGIONAL IMAGE AREA

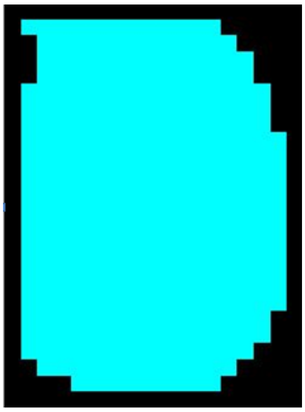


Figure 3.5.2 (AFTER CLOSE)

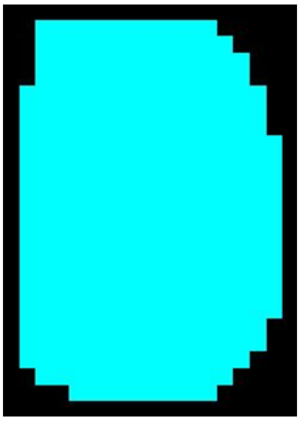


Figure 3.5.3 (AFTER OPEN)

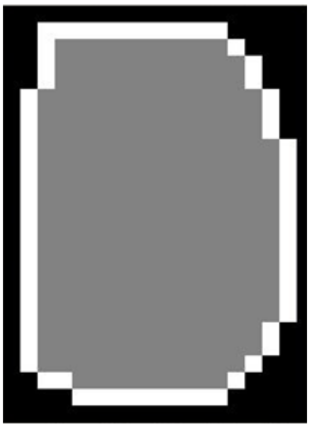


Figure 3.5.4
(FINAL REGION OF INTEREST)

FIGURE 3.5.4 show the whole fingerprint area that is the interest fingerprint image area and its bounded area. The bounded area is the subtraction of the closed area from the opened area.

CHAPTER 4

MINUTIA EXTRACTION

After completing the enhancement and segmentation process now our job is to extract the minutia of the fingerprint image. The minutia extraction stage is divided in to two sub stages such as i) Ridge Thinning and ii) Minutiae Marking

4.1 Ridge thinning:-

The ridge thinning process is used to eliminate the redundant pixels of ridges till the ridges are just up to one pixel wide. This is done by using the following MATLAB's thinning function.

bwmorph(binaryImage,'thin',Inf)

Then the thinned image is filtered by using the following three MATLAB's functions. This is used to remove some H breaks, isolated points and spikes.

bwmorph(binaryImage, 'hbreak', k)

bwmorph(binaryImage, 'clean', k)

bwmorph(binaryImage, 'spur', k)

Figure 4.1.1(IMAGE BEFORE THINNING)

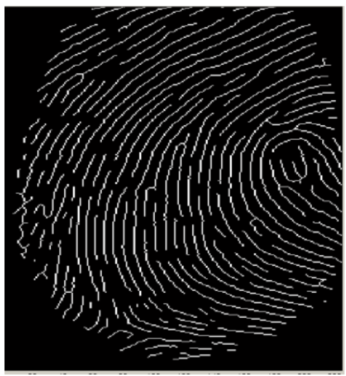


Figure 4.1.2 (IMAGE AFTER THINNING)

4.2 Minutiae marking:-

After completion of fingerprint ridge thinning, minutiae marking is done by using 3 x3 pixel window as follows. In case of minutia marking the concept of Crossing Number (CN) is mainly used.

In 3 x 3 window if the central pixel is 1 and has exactly 3 one-value neighbours, then the central pixel is a ridge branch or bifurcation. i.e Cn(p)=3 for a pixel “p”.

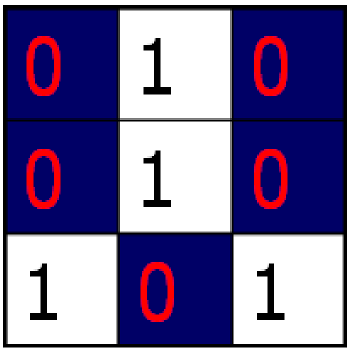


Figure 4.2.1 (BIFURCATION)

In 3 x 3 window If the central pixel is 1 and has only 1 one-value neighbour, then the central pixel is a ridge ending or termination.

i.e Cn(p)=1 for a pixel “p”.

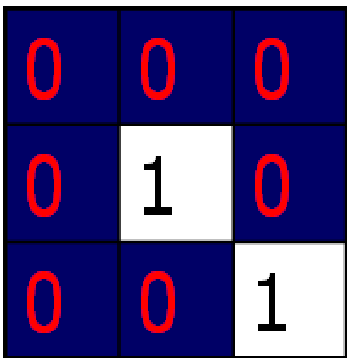


Figure 4.2.2(TERMINATION)

There is an exceptional case where a general branch may be triple counted. If the value of both the uppermost pixel is 1 and the value of the rightmost pixel is also 1. It has another neighbour outside the 3x3 window due to some left over spikes. Then the two pixels will be marked as branches too, but in reality only one branch is located in the small region. Generally this case is very rare.

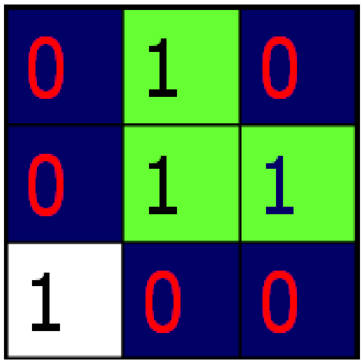


Figure 4.2.3(Triple counting branch)

CHAPTER 5

POSTPROCESSING STAGE

This stage includes two sub stages such as: i) false minutia removal ii) unify termination bifurcation

5.1False Minutia Removal:-

The preprocessing stage can't completely heal the fingerprint image. At this stage different types of false minutia are generated due to insufficient amount of ink or excess inking. False ridge breaks generated due to insufficient ink and the cross connection between the ridges occurs due to over inking. Some of the previous techniques also introduce some spurious minutia points in that image. These types of false minutia are not totally eliminated. So to make the fingerprint recognition system consistent we have to remove all types of false minutia.

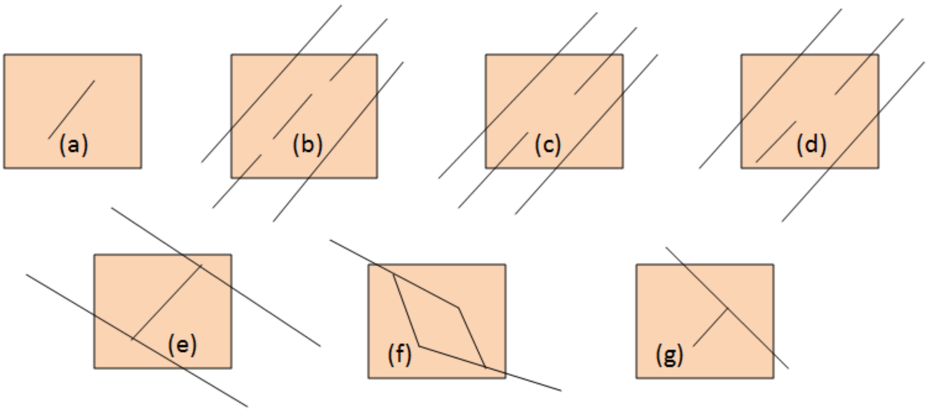
Here first of all we have to calculate the inter ridge distance (D) which is

the average distance between two neighbouring ridges. By using the following formula we can calculate the inter ridge distance (D) easily.

$$\textit{Inter ridge distance} = \frac{sum\ all\ pixels\ with\ value\ 1}{row\ length}$$

Finally an averaged value over all rows gives D.

Seven types of false minutia are specified in following diagrams:



In figure 'a' it is a only one short ridge. In the case of 'b' a third ridge is present in the middle of the two parts of the broken ridge. The two ridge broken points in the 'c' case have a short distance and also nearly the same orientation. In case of 'd' is same as the 'c' case with the exception that one part of the broken ridge is so short that another termination is generated. In case of 'e' a spike falsely connects two ridges. In figure 'f' has in the same ridge the two near bifurcations located. In case of 'g' it is a spike which piercing into a valley.

The following steps are taken into account for the removal of false minutia:

- If the value of d(termination, termination) is less than D & the two minutia are in the same ridge then remove both of them (case a). Here D is the average inter-ridge width.
- If the value of d(termination, termination) is equal to D & the their directions are coincident with a small angle variation & no any other termination is located between the two terminations then we have to remove both of them (case b, c, d)

- If the value of d(bifurcation, bifurcation) less than D & the two minutia are in the same ridge them remove both of them (case e, f)
- If the value of d(bifurcation, termination) is less than D & the 2 minutia are in the same ridge then remove both of them (case g).

Here d(X, Y) is the distance between the two minutia points.

5.2 Unify termination and bifurcation:-

We know one type of minutia can be change to other type easily, coming in contact with the different types of data acquisition conditions. So we have to save them in some form of representation that is both for termination and bifurcation. So each minutia is completely characterized by the following parameters at last:

1) x-coordinate
2) y-coordinate
3) Orientation.
4) Associated ridge

Actually a bifurcation can be broken down to three terminations each having their own x-y coordinates, orientation and an associated ridge.

The orientation for each termination (tx, ty) is estimated by using the following method.

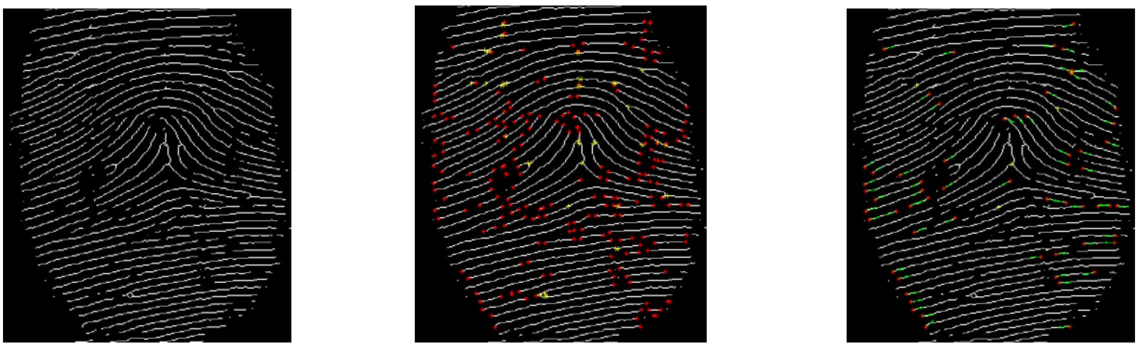
i) first of all we have to track a ridge segment, whose starting point must be the termination and length is D.

ii) Then sum up all the x-coordinates of points present in that particular ridge segment.

iii) After that to get sx we have to divide the above summation with D and sequentially we get sy using the same technique.

Now we can get the direction from the expression: $tan^{-1}\left({sy - ty}/{sx - tx}\right)$

RESULT AFTER MINUTIAE EXTRACTION STAGE



(THINNED IMAGE) **(AFTER MINUTIA MARKING)** **(AFTER REMOVAL OF FALSE MINUTIA)**

Figure 5.2

CHAPTER 6

MINUTIA MATCHING

After testing the set of minutia set of points of two finger print image we perform Minutiae Matching to check whether they belong to the same person or not. It includes two consecutive stages:

i) alignment stage

ii) match stage

6.1Minutiae alignment:-

1) Let I_1 & I_2 be the two minutiae sets given by,

$$I_1 = \{m_{1,} m_2, \ldots . m_M\} \text{ Where } m_i = (x_{i,} \, y_i, \theta_i)$$

$$I_2 = \{m'_{1,} m'_2, \ldots . m'_N\} \text{ Where } m'_i = (x'_{i,} \, y'_{i'} \theta'_i)$$

The ridge associated with each minutia is represented as a series of x-coordinates (x_1, $x_2 \ldots x_n$) of the points on the ridge. A point is sampled per ridge length L starting from the minutia point, where the L is the average inter-ridge length. And n is set to 10 unless the total ridge length is less than 10*L.

So the similarity of correlating the two ridges is derived from:

$$S = \frac{\sum_{i=0}^{m} x_i X_i}{\sqrt{\sum_{i=0}^{m} x_i^2 X_i^2}}$$

At this stage ($x_i \ldots x_n$) and ($X_i \ldots X_n$) are the set of x-coordinates for the two minutia whish we have chosen. And the least possible of 'm' is one of the value of n and N. We will tally the score and if the score is greater than 0.8, then jump to step 2, if not then continue to match the next ridges pair.

2. Here we have to transform each set according to its own reference minutia and then do match in a unified x-y coordinate.

W e are taking M (x, y, θ) as reference minutia which is in I_1. We have to translate and rotate all other minutiae $(xi, yi, \theta i)$ for the finger prints we have taken into account with respect to the M (x, y, θ) according to the following formula:

$$\begin{pmatrix} xi\_new \\ yi\_new \\ \theta i\_new \end{pmatrix} = (TM) \times \begin{bmatrix} xi - x \\ yi - y \\ \theta i - \theta \end{bmatrix}$$

$$\text{Where TM} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The new coordinate system is originated at reference minutia M and the new x-axis is coincident with the direction of minutia M. Here scaling effect is not required, we are assuming two fingerprints taken from the same finger are having nearly the same size.

Therefore we are getting transformed sets of minutiae I_1' & I_2'

6.2 Match stage:-

Generally the two identical minutia are not exactly same due to the slight deformations and also inexact quantization. The algorithm for matching for the aligned minutia patterns should be elastic.

The minutia matching elastic is done by keeping a bounding box around each of the template minutia. If the minutia which is to be matched is within that rectangle box and the direction discrepancy between them is so small, then the two minutia are taken as a pair of matched minutia. Each of the minutia in that template image either has one corresponding minutia or has no matched.

The final match ratio for two fingerprints is given by

$$\text{Match Score} = \frac{number\ of\ total\ matched\ minutiae\ pair}{number\ of\ minutiae\ of\ the\ template\ fingerprint}$$

If the match score is greater than a threshold value which is pre-specified, then the two fingerprints taken are from the same finger.

CHAPTER 7

EXPERIMENTAL RESULTS

7.1 Performance evaluation index:-

There are two types' performance evaluation indexes to determine the performance of a fingerprint recognition system such as:-

7.1.1 False Rejection Rate (FRR): Sometimes the biometric security system may incorrectly reject an access attempt by an authorized user.To measure these types of incidents FAR is basically used. A system's FRR basically states the ratio between the number of false rejections and the number of identification attempts.

FRR

(%) FRR= (FR/N)*100

FR=number of incidents of false rejections

N= number of samples

7.1.2 False Acceptance Rate (FAR): Sometimes the biometric security system may incorrectly accept an access attempt of an unauthorized user. To measure these types of incidents FAR is basically used. A system's FAR basically states the ratio between the number of false acceptances and the number of identification attempts.

FAR

(%) FAR= (FA/N)*100

FA= number of incidents of false acceptance

N=total number of samples

We used A fingerprint database from the FVC2000 (Fingerprint Verification Competition 2000) for testing our experiment performance.

THRESHOLD VALUE	FALSE ACCEPTANCE RATE (In percentage)	FALSE REJECT RATE (In percentage)
7	0.073	7.12
8	0.024	9.44
9	0.012	12.53
10	0	14.32

The false acceptance rate and the false reject rate depends upon the quality of the image whether the quality is good or bad.

CHAPTER 8

CONCLUSION

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The above implementation was really an effort to understand how the Fingerprint Recognition is used in many applications like biometric measurements, solving crime investigation and also in security systems. From minutiae extraction to minutiae matching all stages are included in this implementation which generates a match score. Various standard techniques are used in the intermediate stages of processing.

We have completed our job of preparing a report file on “study of fingerprint recognition system” we don’t know how far we have been able to perform the job accurately. However, we are sure we have always tried to avoid any fault of mistake that may tell on our endeavour. The project emphasizes both the theoretical concept as well as gives in sight in to the practical application program.

Finally, we beg to be excuse for if we come it any mistake in course of writing and preparing the report file.

REFERENCES:

1. D. Maltoni, D. Maio, and A. Jain, S. Prabhakar, “4.3: Minutiae-based Methods’ (extract) from Handbook of Fingerprint Recognition”, Springer, New York, pp. 141-144, 2003.
2. D. Maio, and D. Maltoni, “Direct gray-scale minutiae detection in fingerprints”, IEEE Transactions Pattern Analysis and Machine Intelligence, vol. 19(1), pp. 27-40, 1997.
3. L. Hong, "Automatic Personal Identification Using Fingerprints", Ph.D. Thesis, 1998
4. K. Nallaperumall, A. L. Fred and S. Padmapriya, “A Novel for Fingerprint Feature Extraction Using Fixed Size Templates”, IEEE 2005 Conference, pp. 371-374, 2005
5. Wikipedia link - http://en.wikipedia.org/wiki/Fingerprint_recognition
6. Fingerprint Recognition, Paper by WUZHILI (Department of Computer Science & Engineering, Hong Kong Baptist University) 2002
7. Fingerprint Classification and Matching by Anil Jain (Department of Computer Science & Engineering, Michigan State University) & Sharath Pankanti (Exploratory Computer Vision Group IBM T. J. Watson Research Centre) 2000
8. Handbook of Fingerprint Recognition by Davide Maltoni, Dario Maio, Anil K. Jain & Salil Prabhakar
9. P. Komarinski, P. T. Higgins, and K. M. Higgins, K. Fox Lisa , “Automated Fingerprint Identification Systems (AFIS)”, Elsevier Academic Press, pp. 1-118, 2005.
10. Lin Hong, Student Member, IEEE, Yifei Wan, and Anil Jain, “Fingerprint Image Enhancement: Algorithm and Performance Evaluation” *IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, VOL. 20, pp. 777-787, 1998* .